LBNL-55561

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May 2004

This work was supported by Lawrence Livermore National Laboratory and performed for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098; the Norwegian Research Council through the Strategic Institute Program, Environmentally Favourable Energy Use in Buildings, at the Norwegian Building Research Institute, Project No. 133692/420; and U.S.- Norway Fulbright Foundation for Educational Exchange.

INVESTIGATION OF ROOM VENTILATION FOR IMPROVED OPERATION OF A DOWNDRAFT TABLE

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ABSTRACT

This paper reports a computational fluid dynamics (CFD) study on containment of airborne hazardous materials in a ventilated room containing a downdraft table. Specifically, we investigated the containment of hazardous airborne material under a range of ventilation configurations. The desirable ventilation configuration should ensure excellent containment of the hazardous material released from the workspace above the downdraft table. However, increased airflow raises operation costs, so the airflow should be as low as feasible without compromising containment. The airflow was modeled using Reynolds Averaged Navier Stokes equations with a high Reynolds number k-epsilon turbulence model using the commercial CFD code StarCD. CFD predictions were examined for several ventilation configurations. Based on this study, we found that substantial improvements in containment were possible with a significant reduction in airflow, compared to the existing ventilation configuration.

INDEX TERMS

CFD modeling, downdraft table, ventilation, contamination control

INTRODUCTION

Downdraft tables are used to handle hazardous materials that can become airborne. Ventilation configuration in the room containing the downdraft table affects the downdraft table's performance. However we could not find guidelines in the literature for room ventilation design to ensure good performance of a downdraft table. Furthermore, there are few published studies of performance of downdraft table in a ventilated room. Although both numerical and experimental work has been published investigating the performance of fume hoods (e.g., Lam and Viswanathan 2001), fume hoods are unsuitable for some manipulating operations. The present study investigates possible modifications to the ventilation system of an existing downdraft facility using computational fluid dynamics (CFD).

The facility under investigation remains contaminated from previous use and is inaccessible for detailed experiments. Therefore, any assessment of improving containment and reducing airflow must rely on simulations. The present study uses CFD to test alternate ventilation and geometric configurations for improved containment of the pollutants.

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RESEARCH METHODS

The facility, shown schematically in Fig. 1, consists of two rooms connected by a doorway. In the first room, the change room, the worker puts on protective clothing. This room provides an entrance to the second room, the downdraft room (2.3m x 2.0m x 2.5m high), which contains the downdraft table located against the wall opposite the door. This wall has in it a pass-through window directly above the downdraft table. The contaminated packages are passed into the room through this window and the window is closed when not in use. Currently, air enters the room through a vertical slot in the door behind the worker, and from a rectangular inlet in the ceiling above the table. All airflow exits through the downdraft table. The room has a ventilation configuration that supplies a total of 1700 l/s (3600 CFM) of air to the room. Of this, 1230 l/s (2600 CFM) of air was supplied through an opening in the door connecting the two rooms and 470 l/s (1000 CFM) from the ceiling towards the table. The vertical slot in the door measures 0.81 m x 0.46 m (32" x 18"), with its lower edge located at 10 cm (4 inches) from the floor level. This opening in the door is referred to as the door slot inlet.

The change room was excluded from the computational domain. When the door is closed the details of the airflow within the change room were assumed to have no effect on the airflow in the downdraft room. Airflow entered the downdraft room through the door slot, normal to the door, and was treated as a boundary condition. The airflow from the inlet in the ceiling was assumed to be straight down, and was also a boundary condition.

A simplified model of a worker was included to simulate the effect of flow blockage by the worker on the room airflow. The worker was assumed to be in a protective suit and thermal plume of the worker was neglected (owing to greater than an order of magnitude difference between the plume velocity in still air, and the downdraft room airspeeds). The worker was assumed to be holding an object representing a contaminated package and the package was held above the downdraft table surface and away from the edge in order to represent standard working conditions.

Containment for a given velocity field was investigated by first examining the predicted flow paths of massless particles, and then, in more detail, examining the predicted concentration of tracer gas. The massless particles and the tracer gas were both released from the package and the two additional locations where "worst-case" containment was expected: from the rim of the downdraft table, and the perimeter of the (closed) window in the wall behind the downdraft table. Particle tracks can only show the effects of the mean velocity. Tracks of airborne massless particles give a good indication of whether contaminant will be contained with respect to the mean flow. This is a reasonable <u>minimum</u> criterion to assure containment. Additional mixing in the room from turbulent fluctuations can compromise contamination. To evaluate the additional diffusion caused by turbulence, we simulated a continuous release of a neutrally buoyant tracer gas (as a passive scalar) at the rim of the downdraft tabletop and the perimeter of the pass-through window. Tracer gas has very high diffusivity, much larger than that of particulate contaminants, and its containment represents a <u>maximum</u> criterion for containment of particulate contaminants. We evaluated several modifications to the existing room operation and geometry, by changing the area and airflow from the inlets.

The room containing the downdraft table was modeled using the Reynolds Averaged Navier Stokes equations (RANS) with a high Reynolds number k-epsilon turbulence model. The flow was considered incompressible and isothermal with constant air properties. A finite volume formulation of these equations was solved using the commercial software Star-CD. We have earlier demonstrated very good agreement between CFD predictions of room mixing time and experiments (Gadgil et al. 2003). Our recent research (Finlayson et al. 2004) showed that a RANS model with a second order differencing scheme that suppresses numerical diffusion could provide very good (i.e., within a factor of two compared to experimental measurements) detailed predictions for pollutant dispersion in a room. Justification for our current approach rests on the successful comparison of CFD predictions to experiment.

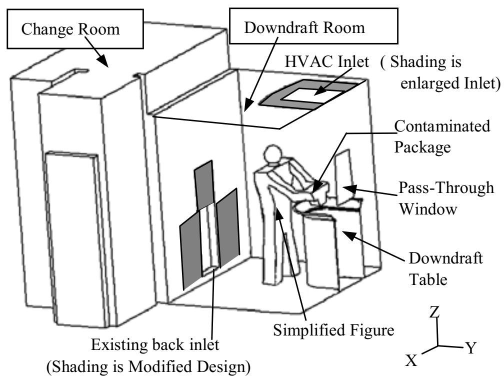

Figure 1*: Facility geometry including the change room, to the left, and the downdraft room to the right (2.3m x 2.0m x 2.5m). The geometry includes the downdraft table, simplified worker figure in a protective suit holding the contaminated package, door inlets, pass-through window, and an inlet in the ceiling.*

The computational grid consists of approximately 670,000 nodes. The grid was locally refined until less than 10% changes were recorded in the overall mean velocities, max and min velocities, and pressure. Predictions for steady state airflow were obtained using SIMPLE (Patankar 1980) algorithm and a second-order differencing scheme. The convergence criterion was considered satisfied when the cumulative normalized residuals dropped below 1.0e-4 for all the variables. We injected a neutrally buoyant tracer gas at the rate of 1.98×10^{-3} kg/s. The tracer gas concentration computations were terminated when the cumulative normalized residuals for the mass transport equation dropped below 5.0e-5.

We now introduce a measure of the contamination spill, S, in the room. The spill was calculated throughout the computational domain excluding the cells inside the downdraft table, and the cells where the tracer gas was released. For a small release rate of tracer the spill was defined as the integral of the tracer-concentration-weighted cell volumes divided by the same volume, normalized by the exhaust concentration. If the release rate of tracer is X kg/s and the fresh air-supply rate is M kg/s and X << M, then we can write

$$S = \frac{\int C dV}{\int dV} \; \frac{M}{X}$$

Mass balance requires that, the concentration at the exhaust must be X/(X + M) at steady state. In an instantaneously perfectly mixed room, the tracer gas concentration in the room will be the same as the concentration at the exhaust. Therefore, for an instantaneously perfectly mixed room C = X/(X + M). When X << M, then C = X/M and the spill measure S = X/M*M/X = 1. If the contaminants are fully contained into the downdraft table S=0, and there is no spill. The spill factor gives a measure of the average concentration of the tracer in the room.

Discussion of existing configuration

First we explored the containment capability of the existing configuration with airflow of 470 l/s (1000 CFM) downward and 1230 l/s (2600 CFM) through the door. This configuration successfully satisfied the minimum criterion for containment, which requires the mean flow to fully contain all the particles within the downdraft table. The airflow pattern is shown in Figure 2. A recirculating airflow pattern can be seen on the left hand side of the table in the x-z view. Figure 3 shows the concentration contours for the existing configuration. The normalized concentration contours are presented in the log scale. In the y-z view, the tracer gas has escaped from the downdraft table, touches the worker's chest and spreads into the room. The x-z view shows that the tracer gas is spread on both sides of the table. The contamination spill for the existing configuration was found to be S=4.22x 10^{-4}. This can be unacceptably high for hazardous materials.

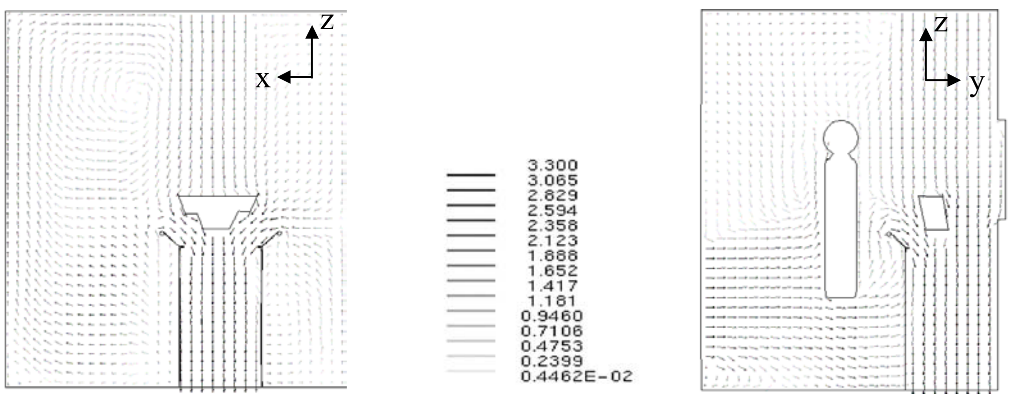

Figure 2: *Velocity predictions for existing configuration along two section planes showing the details of the flow near the worker and on the sides of the downdraft table*

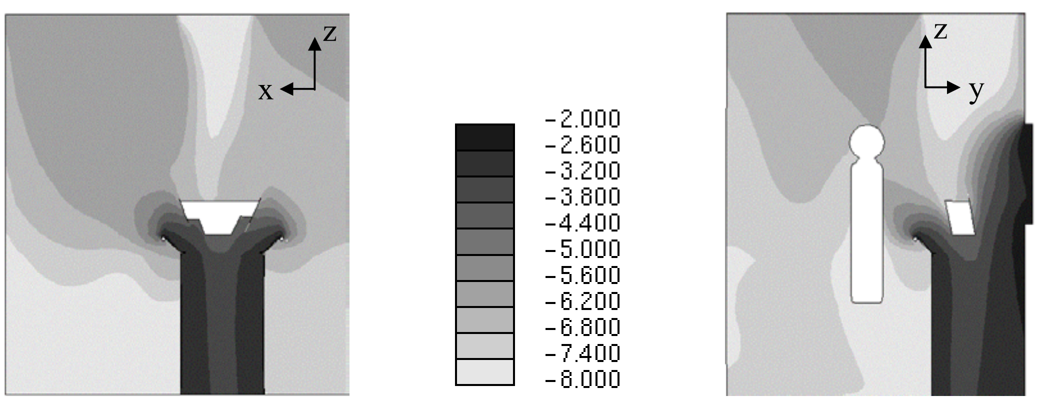

Figure 3: *Tracer gas concentration (log scale) contours for existing configuration*

Alternate configurations

Existing ceiling inlet is shown in Figure 1 as the non-shaded inlet in the ceiling. The large ceiling inlet includes the shaded area shown in Figure 1. Existing door inlet is shown as the non-shaded inlet behind the worker. The large door inlet includes the shaded area on the left and right side of the existing inlet. The width of the existing door inlet is 46 cm (18 inches), and the large door inlet is 73 cm (28.5 inches).

We explored several modifications to the existing room operation and geometry. The changes in geometry are shown in Table 1. Table 2 lists the different geometrical configurations simulated.

***Table 1**: Definitions of inlet geometries*

Inlet type	**Description**	**Area** m^2 (in^2)
Ceiling inlet	Existing	0.32 (500)
	Large	1.07 (1659)
Door inlet	Existing	0.37 (576)
	Large	0.59 (911)

***Table 2**: Summary of different geometry configurations investigated*

Configurations	**Ceiling inlet**	**Door inlet**
A	Existing	Existing
B	Large	Existing
C	Large	Large

Previous work (Finlayson et al. 2003) shows that decreasing the airflow with the same geometry as the existing set up (i.e., configuration A) will reduce the contamination of the room. Ceiling inlet flow was reduced from 470 l/s (1000 CFM) to 380 l/s (800 CFM), and the door flow was reduced from 1230 l/s (2600 CFM) to 755 l/s (1600 CFM).

We examined various flow rates through different inlets for each of the above configurations: 10 cases for configuration A, 19 for configuration B and 12 for configuration C.

RESULTS AND DISCUSSIONS

Simulations with air supply only from the large ceiling inlet were reported in Finlayson 2003. Those results showed that the massless particles released from the rim were not contained by the mean flow, thus failing even the minimum criterion for containment. Flow from the ceiling inlet formed a recirculating flow in the room before entering the downdraft table. This flow pattern is a potential source of contaminant spread in the room.

The present study showed that, the extent of the recirculating flow was minimized when the strength of the flow from the door slot and the ceiling inlet was balanced so that the vertical component of the mean velocity was zero at the level of the downdraft table rim. Aligning the upper edge of the door flow at the level of the downdraft table helps to force air towards the table at the level of the table rim.

Configuration B was simulated with a large ceiling inlet, and the existing door slot. The best solution with this configuration (based on spill measure) improved containment of the tracer gas compared to configuration A. The large ceiling inlet decreased the extent of the recirculating airflow on the left side of the downdraft table. Configuration C has a large ceiling inlet and a large door inlet. The wider door provided a better containment of the tracer gas than configuration B by further suppressing the recirculating flow in the room. Tracer gas concentration contours for this configuration are show in Figure 4. This configuration resulted in a significant improvement in containment compared to the existing configuration. The best run for each configuration is listed in Table 3.

***Table 3**: Spill measures for various configurations*

Configuration	Ceiling inlet l/s (CFM)	Door inlet l/s (CFM)	Spill measure x 10^4
Existing	470 (1000)	1220 (2600)	8.64
A	380 (800)	760 (1600)	4.36
B	470 (1000)	380 (800)	2.42
C	470 (1000)	470 (1000)	2.22

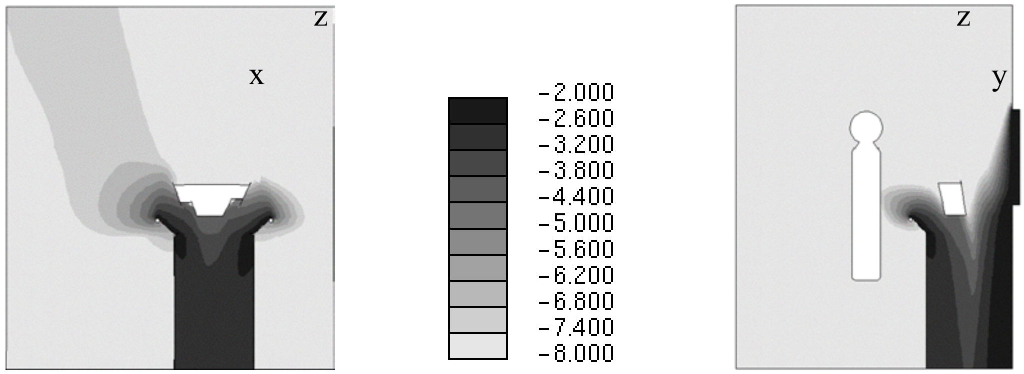

Figure 4 *Tracer gas concentration (log scale) contours for configuration C*

CONCLUSION

CFD simulations showed that substantial reduction in spill measure (74%), and significant reduction in airflow (44%) (and therefore operating costs), could be achieved in the downdraft facility, by modifying the geometry and the ventilation configuration.

ACKNOWLEDGEMENT

This work was partially supported by Lawrence Livermore National Laboratory and the Norwegian Research Council through the Strategic Institute Program "Environmentally Favorable Energy Use in Buildings" at the Norwegian Building Research Institute, Project No. 133692/420; and U.S.-Norway Fulbright Foundation for Educational Exchange. This work was performed at Lawrence Berkeley National Laboratory under U.S. Department of Energy under Contract No. DE-AC03-76SF00098

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